UCRL-ID-133160

Techniques for Enhancing Laser Ultrasonic Nondestructive Evaluation

G. Thomas
R. Huber
J. Candy
D. Chinn
J. Spicer

February 2, 1999

Lawrence Livermore National Laboratory

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

Techniques for Enhancing Laser Ultrasonic Nondestructive Evaluation

Graham Thomas, Robert Huber, James Candy, Diane Chinn,
Professor James Spicer (Johns Hopkins University)

Ultrasonic nondestructive evaluation is an extremely powerful tool for characterizing materials and detecting defects. A majority of the ultrasonic nondestructive evaluation is performed with piezoelectric transducers that generate and detect high frequency acoustic energy. The liquid needed to couple the high frequency acoustic energy from the piezoelectric transducers restricts the applicability of ultrasonics. For example, traditional ultrasonics cannot evaluate parts at elevated temperatures or components that would be damaged by contact with a fluid. We are developing a technology that remotely generates and detects the ultrasonic pulses with lasers and consequently there is no requirement for liquids. Thus our research in laser-based ultrasound allows us to solve inspection problems with ultrasonics that could not be done before. This technology has wide application in many Lawrence Livermore National Laboratory programs, especially when remote and/or non-contact sensing is necessary.

Introduction

Although ultrasonic nondestructive evaluation is a mature technology, there continue to be advances that expand its role in material characterization, manufacturing process control, defect detection, and life cycle management. Ultrasonics is evolving with improvements such as higher frequencies to sense smaller defects, modern signal processing methods to increase sensitivity, classification algorithms for defect characterization and modern imaging techniques to display defects. Despite these advances, a universal limitation of traditional piezoelectrically generated and detected ultrasound is the need to transmit the acoustic energy from the transducer into the part through a liquid, most often water. For many parts and materials, particularly those of interest to the Department of Energy, it is extremely desirable to eliminate this couplant. Laser generation and detection of ultrasonic energy provides a method to perform remote, non-contact ultrasonics [1]. It allows ultrasonic evaluations in high temperature and radioactive environments, in applications where access is restricted such as in a vacuum, and on materials that would be damaged by couplant contamination. For ultrasonic inspections on radioactive materials any couplant used becomes hazardous waste, and thus laser ultrasonics reduces hazardous waste since no couplant is required.

Other advantages of laser-based ultrasound include the generation of various acoustic modes from a single laser pulse, the alignment of the laser beam to the part surface is not critical, and the wide-bandwidth detection capability of certain types of interferometers. Also lasers with extremely short, femtosecond pulse lengths generate acoustic signals at GigaHertz (GHz) frequencies. The extremely short wavelengths of the GHz pulses allow the measurement of nanometer layer thicknesses, and detection of extremely small defects.

New applications for laser-based ultrasound continue to be implemented as breakthroughs in the technology occur, but there is still much to be understood before its full potential can be realized. A significant limitation of laser-based ultrasound is its poor sensitivity as compared to the sensitivity of traditional piezoelectric-based ultrasonics. To improve the sensitivity, research is being pursued in the areas of improved ultrasonic generation, better detectors, and in signal processing to make laser ultrasonics viable. Also beam-forming and other signal processing techniques have been developed to improve the defect detection levels of laser acoustics. Significant improvements in both the generation and detection aspects of Lawrence Livermore National Laboratory's laser-based ultrasound capability were realized during this project. Laser based ultrasound will continue to increase its role in nondestructive evaluation as research solves the sensitivity limitation.

Progress

We are exploring the physics of generating acoustic energy with a laser pulse, and the methodology of detecting ultrasonic signals with laser interferometers. Our goal is to expand the role that ultrasonics plays in supporting the Laboratory's programs by implementing laser generation and detection of acoustic energy.

Signal and Image Processing and Beam Forming

Our primary contribution to the field of laser based ultrasonics has been in developing signal and image processing techniques to improve its sensitivity. We have demonstrated the benefits of several signal processing approaches that greatly improve the ability of laser based ultrasonics to find defects. A model based signal processing technique has been developed and tested [2,3]. This technique starts with a computer code that predicts the acoustic signals that are generated in a prescribed material based on the laser's parameters. The predicted ultrasonic signal becomes the model for signal processing of the real ultrasonic data. A code (WAVER) developed at the Johns Hopkins University [4] allows modeling of materials and laser configurations that are of interest to LLNL programs. The model based signal processing procedure was implemented on ultrasonic signals generated with a Nd:YAG laser and detected with a Michelson interferometer [5]. This sensitivity improving technology is significant since it allows the application of laser based ultrasonics for materials where acoustic attenuation is large.

Beam forming is another signal processing approach that improves defect detection. Beam forming improves defect detection sensitivity by viewing the defect from several directions and combining the information from each direction in a manner to accentuate the defect's image. First we modeled the acoustic beam from an array of senders and receivers. Then we confirmed the models by implementing the beam forming algorithms on experimental data. The experiment consisted of configuring a synthetic laser ultrasonic array to gather the data from a specimen with a reference defect and rendering an image of the known defect with the beam-forming algorithm. This method enhances the detection and display of defects by combining the information from an array of sensors [5,6] and therefore increases the sensitivity of laser based ultrasonics.

We developed an extension of beam forming called matched-field imaging of the laser-based ultrasound signals. This signal processing technique uses a novel correlation canceling approach to eliminate noise, thereby increasing the signal-to-noise ratio of the experimentally obtained data. A critical component of this technique is the reference signals. Reference signals from a part can be obtained, and then subsequent signals from the same, or similar parts would be compared to the reference signals to look for differences. The benefit of matched field imaging was experimentally demonstrated on an aluminum sample. For an aluminum plate containing no flaws, all of the ultrasound propagating through the thickness will be bulk (eg. longitudinal or shear) waves, affected only by the boundaries of the materials. The reference signal obtained from an interferometer used to detect the ultrasound is R(t). This signal can be used as the reference signal in correlation cancellation. For a part with flaws, the ultrasound will interact with the flaws and will give rise to signals containing information about the flaws.

The measured data S(t), and the canceled data P(t) are:

$$S(t) = R(t) + F(t) + N(t),$$

$$P(t) = S(t) - R(t) = [R(t) + F(t) + N(t)] - R(t) \approx F(t)$$

where F(t) is the component of the signal corresponding to ultrasound interacting with the flaw and N(t) is the noise. The noise N(t) is considered to be similar in both the reference and the measured data. The correlation canceling technique uses the reference data, comparing it to the measured data. Features that correlate strongly between the two sets of data are considered to have no information about any flaws in the materials and are removed leaving just the information of interest, in this case information concerning the hole, in the "canceled" signal. The remaining features are considered to have information relating to the flaw, and are enhanced by the removal of noise and signals which are not of interest. Eleven linear scans of through transmission data, generated by a Nd:YAG pulsed laser and detected by a Michelson interferometer, were obtained from a 9.5 mm thick aluminum plate. Each scan consists of 21 amplitude vs. time waveforms. Figure 1 shows the source and detection locations for these scans. There were 11 source locations spaced 2 mm apart, and 21 detection locations spaced 1 mm apart. The source position was held fixed for a scan (21 different detection locations), and then moved two mm for the next scan. A 1/16 inch (1.6 mm) diameter hole was then drilled into the aluminum plate to simulate a defect, and the plate was scanned over the same region that was scanned prior to the hole being drilled. The waveforms obtained after the hole was drilled, shown in Figure 2a, were processed with the reference waveforms obtained before the hole was drilled, Figure 2b. The optimal correlation canceling scheme extracted just the hole information as shown in Figure 2c with a single channel result shown in 2d. Processing yielded the canceled signal from the pre-hole and post-hole data. These signals generate images, which show the effects of the presence of the hole on the ultrasound for different source and detector locations, Figure 3. Our results demonstrate that signal and image processing significantly improve the sensitivity of laser based ultrasonics.

Facility

A world class laser based ultrasonic laboratory has been assembled during this LDRD project. We began with a Michelson interferometer and a small Nd:YAG laser for laser-based ultrasound work. Our first improvement to the hardware was a correction circuit for the Michelson interferometer which greatly increased its stability. Also modifications to both the electronic and mechanical components were made. We added a LISOR (Light In, Signal Out Receiver) interferometer to expand our detection capabilities. This instrument is a Fabry-Perot based system that complements the earlier path stabilized Michelson interferometer. The Michelson requires highly reflective surfaces to sense the ultrasonic signal whereas the Fabry-Perot works on less reflective surfaces. The LISOR system includes an interferometer and a laser. The laser is a frequency doubled Nd:YAG, which has an output power of 200 mW at a wavelength of 532 nm. Fabry-Perot interferometers can function with light scattered from rough surfaces since they work with multiple speckles. Michelson interferometers work with a single speckle only, which limits their use to polished surfaces. The LISOR system has been used successfully in the laboratory to detect ultrasound propagating through various materials and specimens. The Michelson interferometer has a frequency range of DC to 40 MHz while the Fabry-Perot has a frequency range of 3 to 100 MHz. The Michelson measures surface displacement while the Fabry-Perot measures the surface velocity, and thus their outputs for the same ultrasounic event will appear different. Together, these interferometers provide a full range of detection capabilities for most ultrasonic evaluation needs.

Another addition to the laser ultrasonic facility was an improved ultrasonic generating laser that provides more light energy, a higher repetition rate and a uniform spot. This Nd:YAG source laser can operate at two wavelengths and has much better beam quality than the smaller Nd:YAG laser. This laser generates optimal ultrasonic signals that are needed to implement the model-based signal processing algorithms.

As part of the data acquisition and imaging effort, we acquired computer controlled motion stages. These stages include two translation stages and one rotation stage that allow the movement of specimens for scanning. Data acquisition and motion control programs have been written to control the stages and capture the ultrasonic signals. The signal-processing and beam-forming algorithms are combined with the motion-control software to render images of defects from the data obtained when specimens are scanned. Most nondestructive evaluation tasks require an image of the defects and the scanning capability is needed to generate the ultrasonic images.

Fiber Optics

Fiber optics are a significant development for laser based ultrasonic implementation since they allow the lasers and other equipment to be located away from the object under test.

The laser light can then be transmitted from one location to the other, completely contained in the fibers, thus eliminating the hazards of transmitting beams through the air. Fiber optic configurations have been developed and implemented in several applications. The first such activity involved placing the probe arm of the Michelson interferometer in a single mode optical fiber. Since the Michelson interferometer operates on a single speckle of light, single mode fiber is required. Figure 4 is a comparison of signals obtained using the Michelson interferometer for: 1) optical fiber probe path and 2) no optical fiber. The two waveforms were generated by a thermoelastic source in an aluminum plate. The source and detection lasers were on opposite sides of the specimen. Although there is a reduction in the signal-to-noise ratio of around 50% for the fiber because light is lost when coupling to fiber, the waveforms are quite similar, which proves the feasibility of performing laser ultrasonics with fiber optics. Increasing the detection laser power would increase the signal-to-noise ratio for this experiment.

The Fabry-Perot interferometer (LISOR) works with fiber optics. Initially the illuminating laser was transmitted through air and only the light reflecting off the specimen was transferred to the Fabry-Perot interferometer in a mulitmode fiber. The Fabry-Perot interferometer can process more than one speckle at a time, and so multimode fiber can be used. To increase the flexibility of this detection system, an optical fiber cable 20 meters long transmits the laser light from the interferometer's laser to the specimen, allowing the testing of items up to that distance away from the laser and interferometer. Fiber optics have the advantages of allowing large distances between equipment and test location, providing access to hostile or hard to reach environments, changing test configuration easily, and eliminating the need for line of sight between laser and part. Then we demonstrated that the light from the part illuminating source laser could also be transmitted through a multimode fiber. Thus all of the travel path of the laser light can be contained in optical fiber. Now the light is human safe and easily generated a distance away from the specimen.

Applications

The laser-based ultrasound laboratory has the capability to evaluate a wide variety of materials, and has looked at materials including aluminum, stainless steel [7], uranium, ceramics, and paper. This capability will allow us to support programs at LLNL such as Weapons, Lasers, NAI and Energy. The following section briefly describes programmatic applications that resulted from this research.

Process Control for Laser Cutting

Ultrasonics is an extremely valuable sensor for process control. The speed at which ultrasonic testing can acquire measurements facilitates feed-back control for machining operations. We selected a process control problem as a vehicle to direct our research. The process was a laser cutting application based on a laser that produces very short duration pulses. A sensor was needed to detect when the laser cuts through the part. The pulses from the cutting laser generate acoustic signals that contain information about the cutting process and specifically when the laser cuts through.

Our first challenge was to understand the phenomenon, and the types of ultrasonic waves that are generated. We modeled the system with a computer code [4] that calculates the expected ultrasonic signal based on laser parameters and the material properties and geometry. Initial tests were run on a thin stainless steel plate [7]. The cutting laser beam was directed at the plate and the Michelson interferometer detected the ultrasound generated by the cutting beam. The Michelson interferometer detected both bulk and surface waves. In one set-up, detection was performed on the side of the plate opposite that on which the cutting beam was incident for the capture of bulk waves. In the other set-up, the cutting beam and the interferometer beam were both incident on the same side for the capture of the surface waves. This configuration proved to be optimal for process monitoring. Next, the Michelson interferometer was configured to detect the ultrasound generated by the cutting laser in a real part [5]. At the start of the cut, a clear signal was seen, and as predicted, this signal disappeared by the time cut-through occurred. This loss of acoustic signal is the parameter selected for sensing when the laser had cut through the part.

After successfully detecting the signals generated by the cutting laser with the Michelson interferometer, the next stage of this work involved switching to a Fabry-Perot interferometer for ultrasound detection. Whereas a strip of reflective tape was required at the detection site when using the Michelson interferometer, no tape is needed for the Fabry-Perot, and thus detection on non-specularly reflecting surfaces is possible. This process monitoring application involves non-specularly reflecting surfaces. Another advantage of the Fabry-Perot interferometer is that the light is transmitted to and from the cutting chamber by optical fibers 20 meters in length. We tested the sensitivity of the Fabry-Perot to laser generated ultrasound by thermoelastically generating acoustic energy in an aluminum plate with a Nd:YAG laser and detecting with the Fabry-Perot. The waveform for this case is shown in Figure 5. The next step was to detect the ultrasonic energy with the Fabry-Perot interferometer on a stainless steel surrogate part, to more nearly mimic the testing on actual parts to be cut by the cutting laser. Figure 6 shows a waveform signal-averaged from 10 laser pulses. The stainless steel part was a thin shell, and the waveform shows a dispersive plate wave. Once the feasibility was demonstrated the program funded a development effort implementing this feed back control sensor. It is a standby option and could be implemented in production if needed.

Laser-based Ultrasound Sensor for Paper Manufacturing

The DOE has an initiative to reduce energy consumption in the largest industries in the United States. Paper manufacturing is one such industry. Lawrence Berkeley Laboratory (LBL) funded us to collaborate with them on developing a laser ultrasonic sensor. Real time process control afforded by this sensor will increase the quality of the paper product and reduce energy consumption. The researchers from LBL are working with the Ultrasonics Group at LLNL, to demonstrate ultrasonic characterization of paper as it is being processed. Our sensing approach generates plate waves in the paper with a laser, and a Fabry-Perot interferometer detects the ultrasonic signals. Changes in acoustic velocity and attenuation signify variations in the paper processing. This project is ongoing and may result in a demonstration at a factory.

Sensor for finding inclusions in molten aluminum

One task of a cooperative research and development agreement (CRADA) between the DOE and the Big 3 automobile manufacturers is to explore nondestructive evaluation techniques to improve the casting of aluminum. Nondestructive evaluation could play a crucial role in improving cast parts by detecting impurities in the molten feed stock prior to casting. These impurities often cause defective castings. The defective castings then increase manufacturing costs and as well as energy consumption. Ultrasonic evaluation will sense the presence of impurities but traditional piezoelectric probes will not survive the high temperatures. Laser-based ultrasound offers a means of testing molten materials since it is a non-contact technique. We are funded to demonstrate laser generation and detection of ultrasound in molten metal. A furnace that has a port to pass the laser light has been installed in the laser based ultrasonic laboratory. Aluminum will be melted in the furnace and laser generated and detected ultrasound will interrogate the molten metal. The acoustic energy reflected by impurities in the molten material will be detected by an interferometer.

This system may remotely monitor the quality of raw material feeding the casting process and sense problems before defective parts are produced.

Summary

Laser generation and detection of ultrasonic energy is an important addition to the nondestructive evaluation technologies. Several tasks were accomplished during this project. Fundamental and applied research was conducted in the areas of laser generation, laser detection, signal processing, fiber optics, and beam forming. We combined beam-forming methods with linear array techniques to improve the imaging of defects. We implemented fiber optic transmission of light to make the technology safer and expand its applications. This project produced a world class laser-based ultrasonic facility. Our capabilities include laser generation and laser detection systems, computer controlled data acquisition equipment and a suite of signal processing software. We improved the sensitivity of laser based ultrasonics by developing algorithms to model the laser-material interaction, to apply beam forming methods to array data, and to render images for improving defect detection.

Laser based ultrasonics has been applied to LLNL programs. Also outside agencies have funded us to develop laser based ultrasonic techniques. We developed a remote sensor for monitoring a laser cutting process for the weapons program. We are working on a CRADA with the automobile manufacturers to evaluate molten aluminum ultrasonically with laser generation and detection of the acoustic energy. And Lawrence Berkeley National Laboratory approached us to help them with the development of a laser-based ultrasonic process monitoring sensor for the paper industry. Laser-based ultrasonics is an enabling technology that has been implemented for one laboratory program and will benefit many others.

Future Work

Although laser-based ultrasonics is beginning to be supported by Laboratory programs, there are advances in the technology that will lead to more applications. Refinement of the computer code that calculates the ultrasound generated in materials from laser pulses will allow model-based processing on more complex parts, such as parts containing a variety of defects. Continued advances in the signal and image processing aspect of the work will lead to increases in the signal-to-noise ratios of experimentally obtained data, and thus will allow laser-based ultrasonic testing on a wider variety of materials and parts. Improvements in lasers and optics will benefit the field and should be pursued.

A limitation of traditional ultrasonics is the upper frequency that can be achieved with piezoelectric transducers. Higher frequencies produce shorter wavelengths which allow us to sense smaller defects. Since very short pulse lasers generate extremely high frequency ultrasonic energy, we can develop methods to detect very small defects.

Along with generating these high frequency signals there needs to be a way of detecting them. Recent work by Fiedler [8] reports on an interferometric technique for detection. He also lists a number of references in the area of laser generated high frequency ultrasound. This includes acoustic frequencies over 100 MHz and well into the GHz. These high frequencies are required when working with materials whose characteristic dimension or defect size is below 1 micrometer. A difficulty with using these high frequencies is that the attenuation is significant. The technology developed at LLNL will help overcome this signal-to-noise limitation. This new area of research has the potential for meeting the high spatial resolution demands emerging in the National Ignition Facility, Extreme Ultraviolet Lithography, and Weapons applications.

Acknowledgements

Work performed under auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract no. W-7405-ENG-48.

References

[1] C. B. Scruby and L. E. Drain, *Laser Ultrasonics, Techniques and Applications.* New York: Adam Hilger, 1990.

[2] J. V. Candy, G. H. Thomas, D. J. Chinn, and J. B. Spicer, *Laser Ultrasonic Signal Processing: A Model-Reference Approach. J. Acoustic. Society Am.,* **100**, (1), 1996.

[3] R. D. Huber, D. J. Chinn, G. H. Thomas, J. V. Candy, and J. Spicer, *Model-Based Signal Processing for Laser Ultrasonic Signal Enhancement.* **Review of Progress in Quantitative Nondestructive Evaluation 16, 757-764,** Plenum Press, New York, 1997.

[4] J. Spicer, *Laser Ultrasonics in Finite Structures: Comprehensive Modeling with Supporting Experiment.* **Ph.D. Thesis.** Baltimore: Johns Hopkins University, 1991.

[5] G. H. Thomas, D. J. Chinn, R. D. Huber, J. V. Candy, and J. B. Spicer, Techniques for Enhancing Laser Ultrasonic Nondestructive Evaluation, Lawrence Livermore National Laboratory UCRL-ID-129207, Livermore, CA, 1998.

[6] D. Johnson and D. Dudgeon, *Array Signal Processing: Concepts and Techniques.* New Jersey: Prentice-Hall, 1993.

[7] D. J. Chinn, R. D. Huber, D. D. Scott, G. H. Thomas, J. V. Candy, and J. B. Spicer, New Techniques Laser Ultrasonic Testing, Lawrence Livermore National Laboratory UCRL-ID-125476, Livermore, CA, 1997.

[8] C. J. Fiedler, The Interferometric Detection of Ultrafast Pulses of Laser Generated Ultrasound, Wright Laboratory, WL-TR-96-4057, 1996.

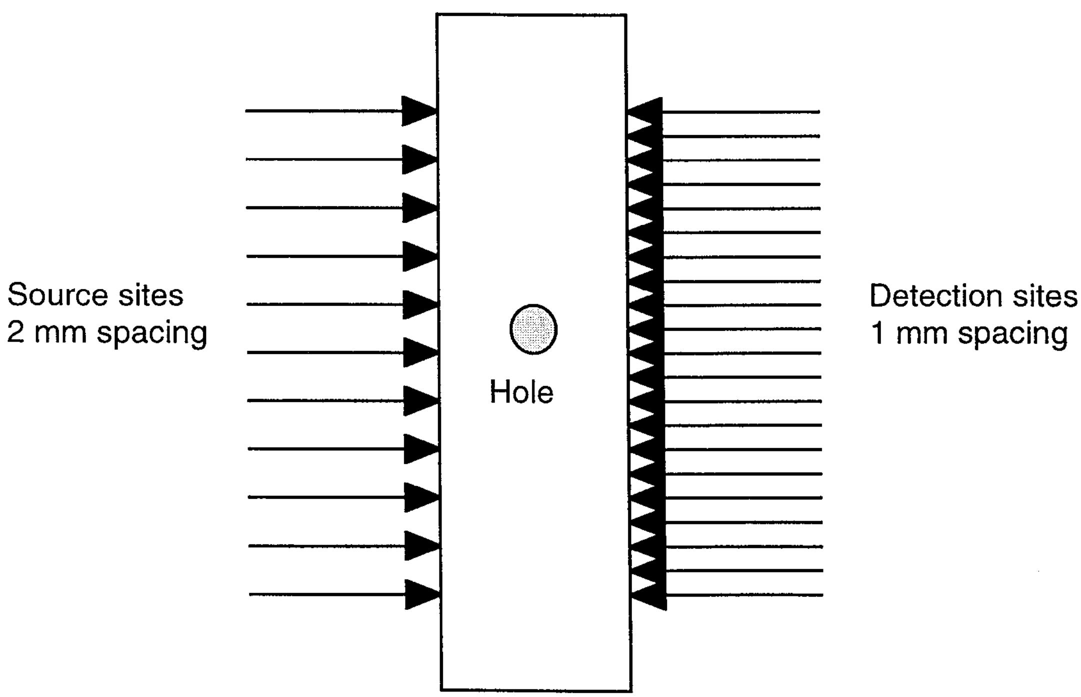

Figure 1. Source and detection sites for laser ultrasonic generation and detection on an aluminum plate with a single 1.6 mm diameter hole. Data obtained before and after the hole was drilled were used to generate the images in the following figures.

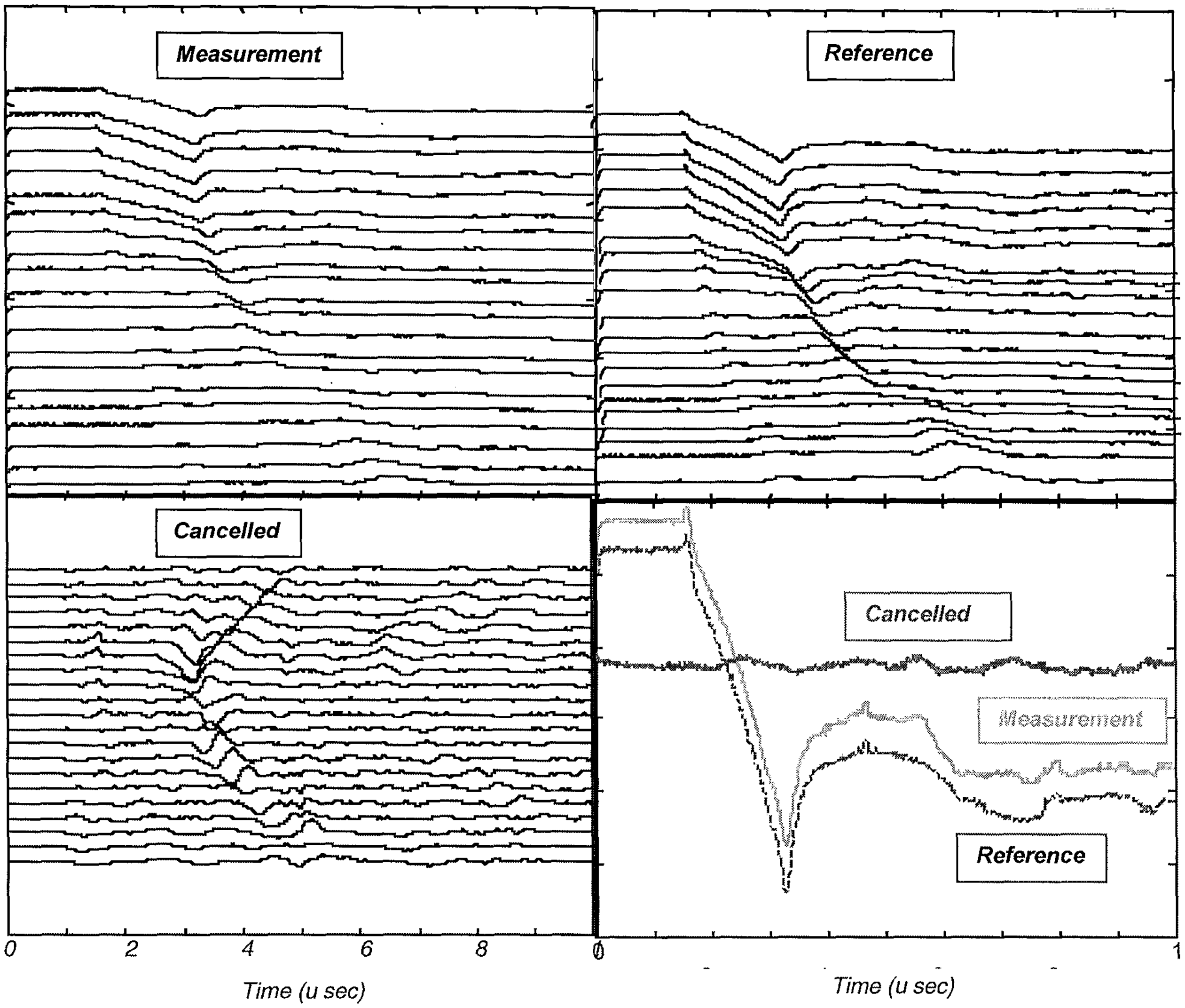

Figure 2. Laser Ultrasonic Correlation Cancellation for Enhanced Flaw Detection. Top left plot shows the waveforms obtained after the hole was drilled (measurement) for one source location. Top right signals were obtained prior to drilling of the hole (reference). Bottom left plot displays the cancelled signals. Bottom right display shows an individual wave for the pre and post drilled cases with the corresponding cancelled signal. The "canceled" signal contains only the information corresponding to the ultrasound that has interacted with the hole, since the contribution from the source that would obscure the hole is eliminated. (Figure 2a-d are from top left to bottom right).

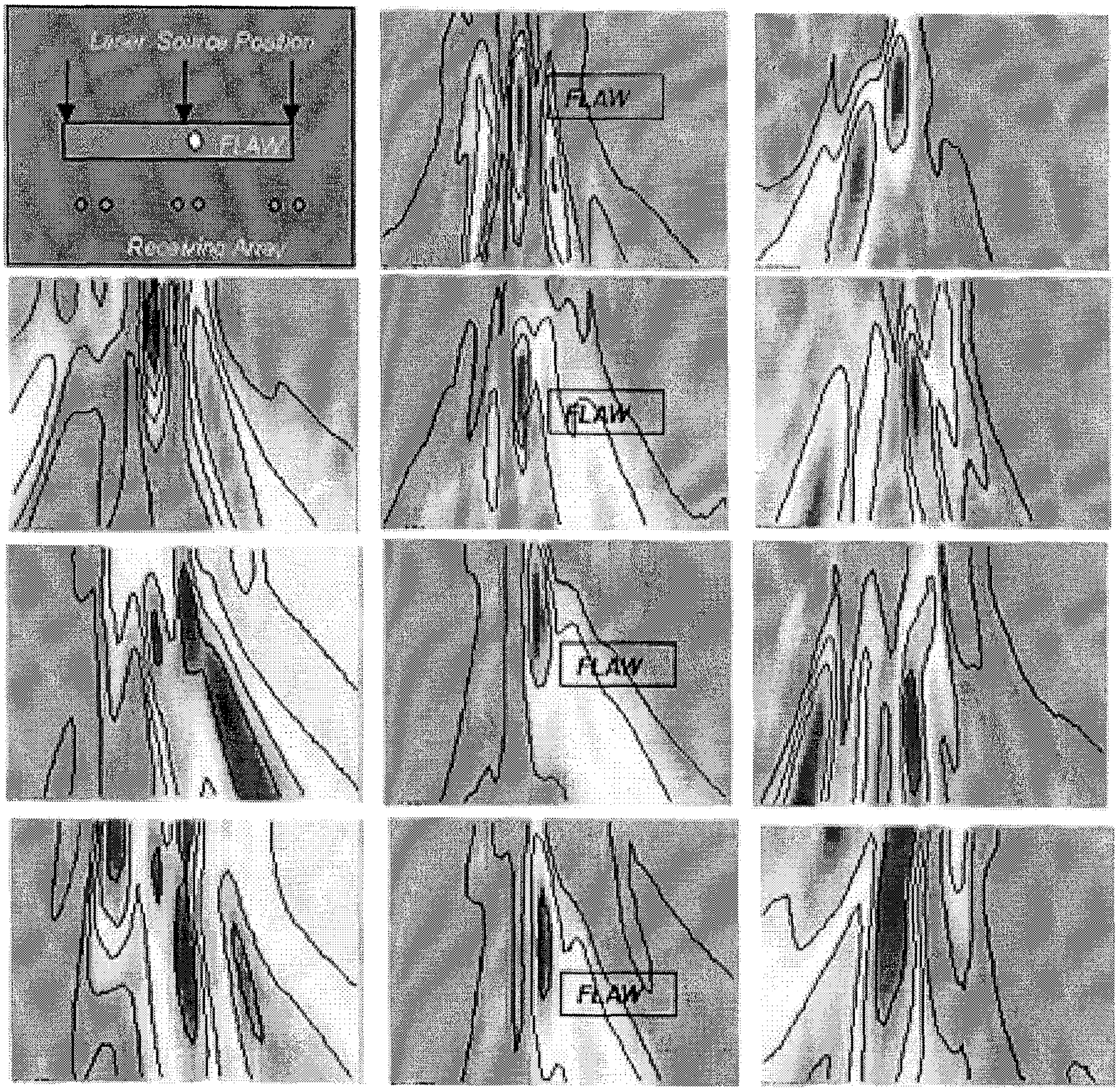

Figure 3. Images obtained from Correlation Cancellation. The 11 images correspond to 11 different source locations for linear scans on the aluminum plate. The hole appears sharpest when the source is directly over the hole.

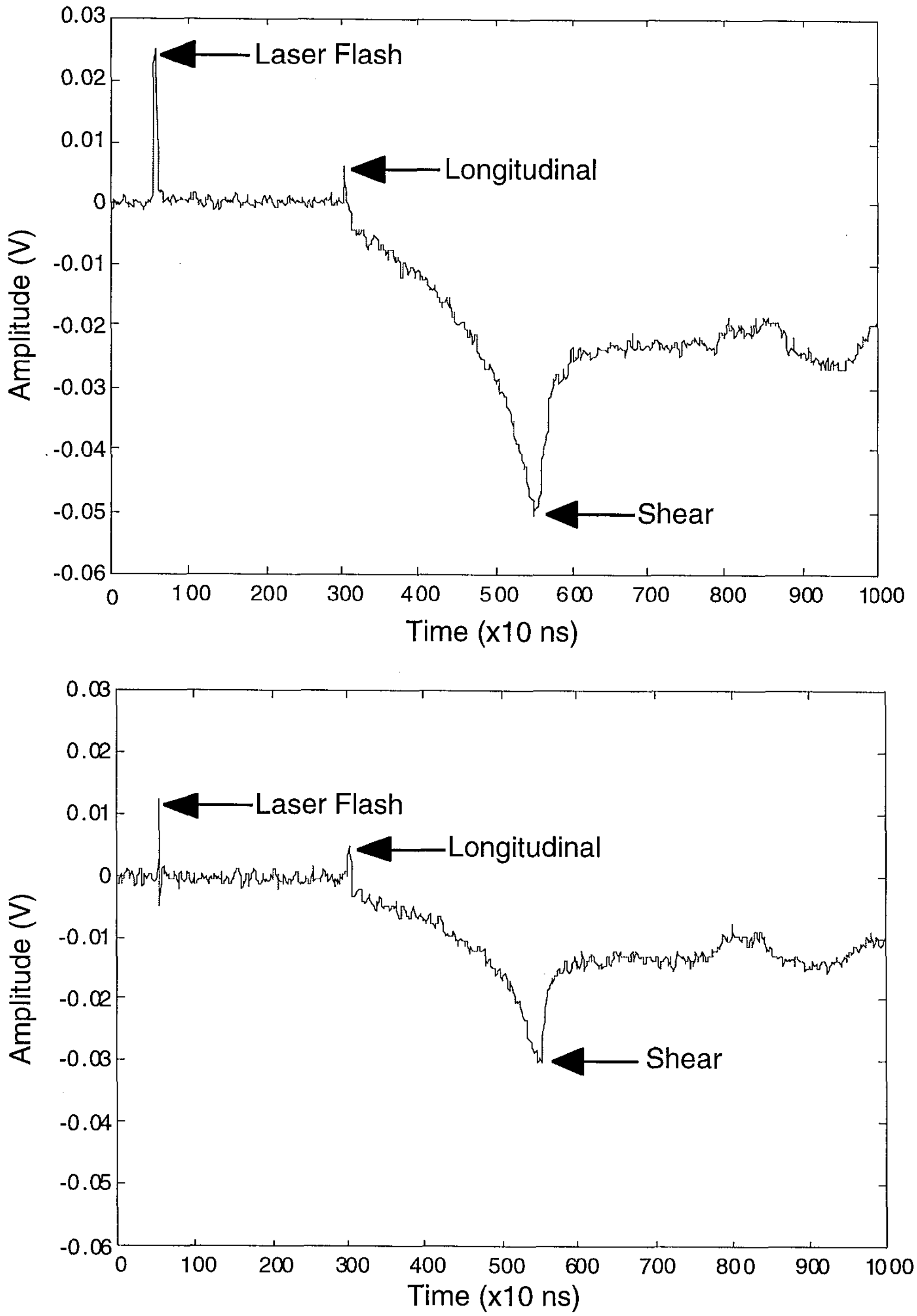

Figure 4. The upper waveform was captured using the Michelson interferometer with no fiber, while the lower was captured using fiber in the probe arm. A decrease in signal-to-noise ratio of around 50% is seen, resulting from a loss of light when coupling to the optical fiber. Both waveforms are through transmission on epicenter in aluminum.

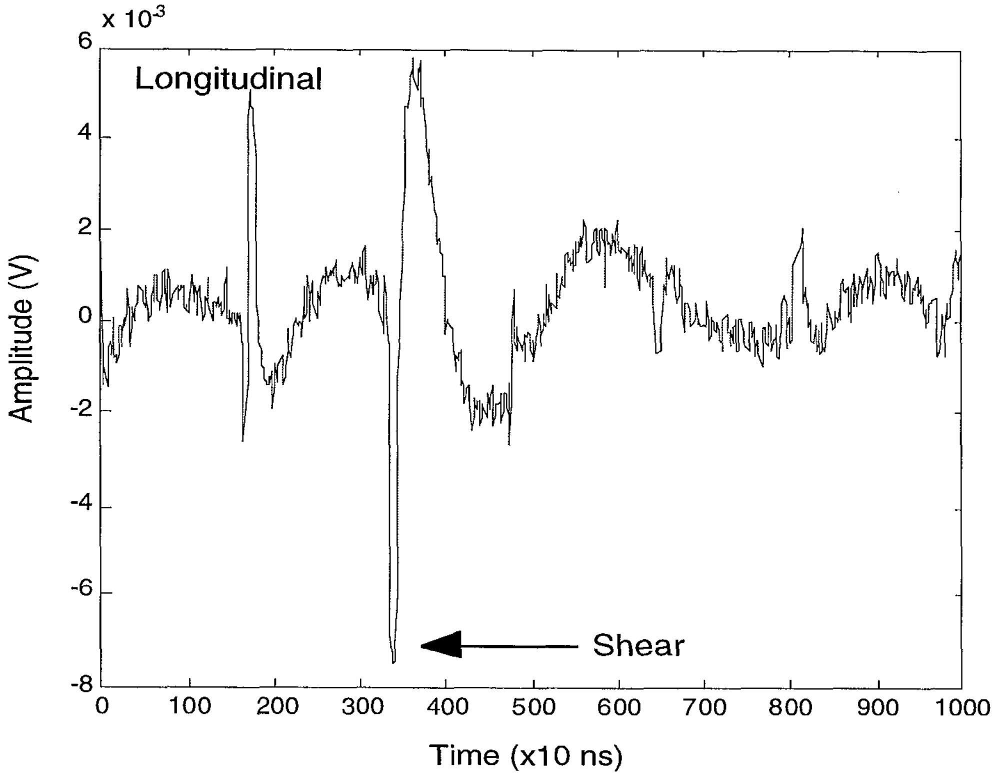

Figure 5. Fabry-Perot interferometer detected signal of laser generated ultrasound. This is a through transmission on epicenter case in an aluminum plate for a thermoelastic source.

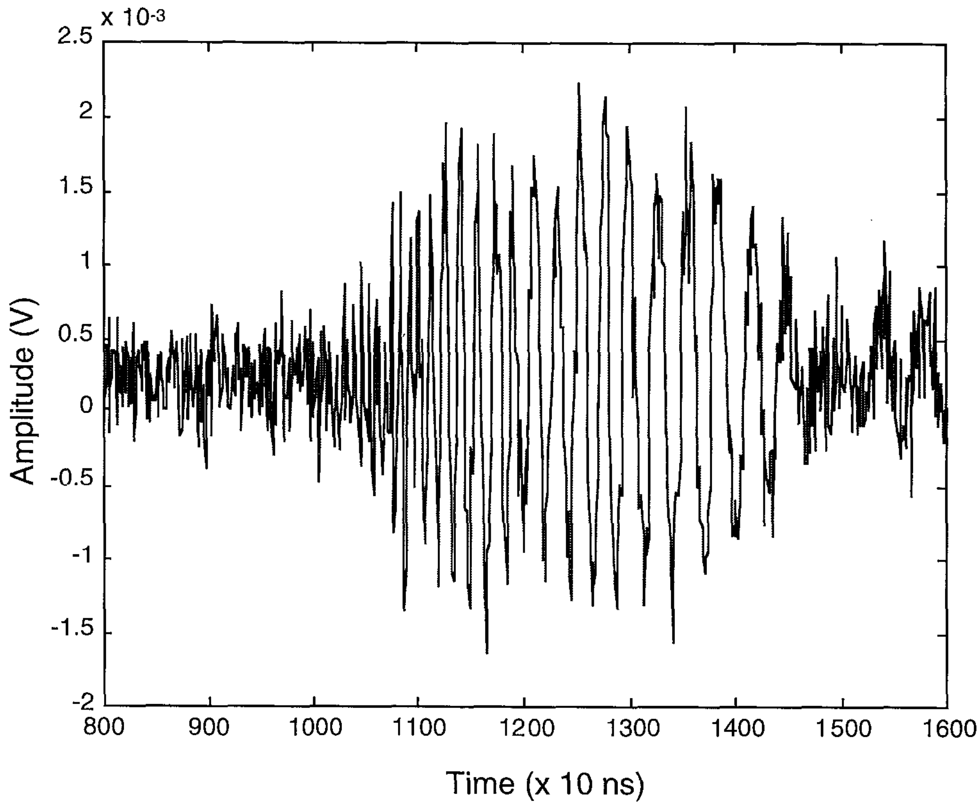

Figure 6. Fabry-Perot interferometer detected signal of laser generated ultrasound in a stainless steel shell. The waveform shows the dispersion of the plate waves, i.e. the high frequencies travel faster than the low frequencies.